

**SPLIT MANDREL VS. SPLIT SLEEVE COLDWORKING:  
DUAL METHODS FOR EXTENDING THE FATIGUE LIFE OF METAL STRUCTURES**

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**ABSTRACT**

It is common practice to use split sleeve coldworking of fastener holes as a means of extending the fatigue life of metal structures. In search of lower manufacturing costs, the aerospace industry is examining the split mandrel (sleeveless) coldworking process as an alternative method of coldworking fastener holes in metal structures. The split mandrel process (SpM) significantly extends the fatigue life of metal structures through the introduction of a residual compressive stress in a manner that is very similar to the split sleeve system (SpSl). Since the split mandrel process is significantly less expensive than the split sleeve process and more adaptable to robotic automation, it will have a notable influence upon other new manufacture of metal structures which require coldworking a significant number of holes, provided the aerospace community recognizes that the resulting residual stress distributions and fatigue life improvement are the same for both processes. Considerable testing has validated the correctness of that conclusion. The findings presented in this paper represent the results of an extensive research and development program, comprising data collected from over 400 specimens fabricated from 2024-T3 and 7075-T651 aluminum alloys in varied configurations, which quantify the benefits (fatigue enhancement and cost savings) of automating a sleeveless coldworking system.

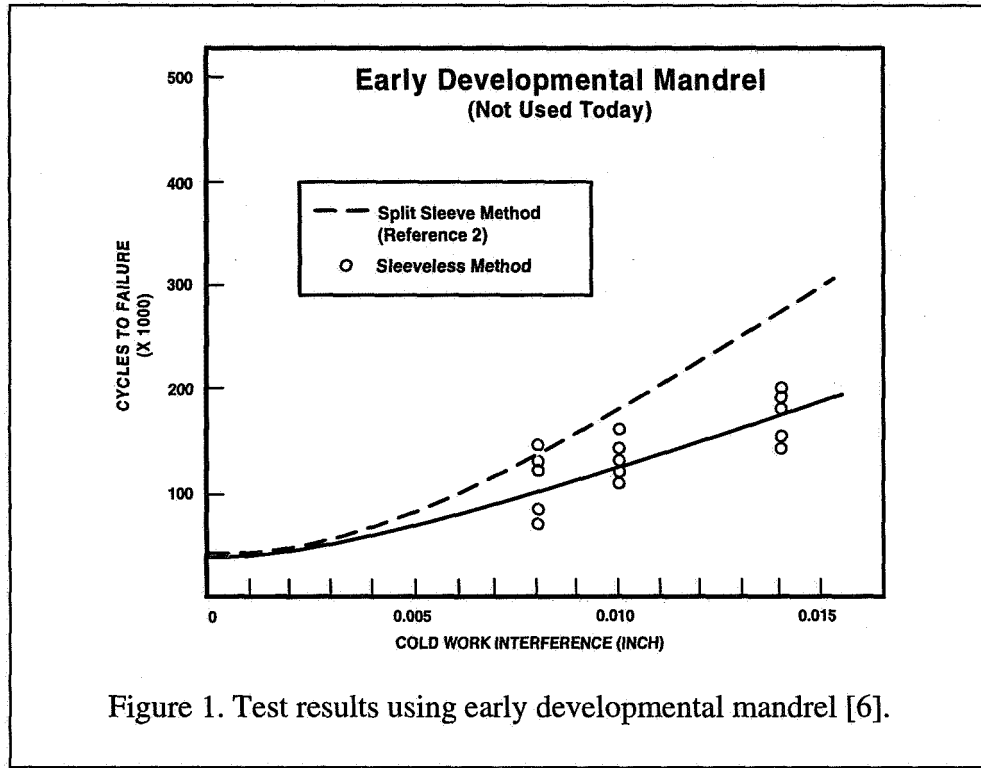
# **SPLIT MANDREL VS. SPLIT SLEEVE COLDWORKING: DUAL METHODS FOR EXTENDING THE FATIGUE LIFE OF METAL STRUCTURES**

## **INTRODUCTION**

In light of today's emphasis on economy, engineers must make informed decisions that influence the costs associated with the manufacture of new, and retrofit modification of aging aircraft structures. The manufacturing costs associated with such programs often drive decisions to sacrifice long term design life in order to minimize short term costs associated with manufacturing or repair. One classical fatigue problem has been that associated with the stress concentration found at fastener holes. For several decades, the aerospace industry has utilized numerous techniques to introduce a beneficial compressive residual stress at the hole in order to minimize the effects of the discontinuity. Many of these methods, including roller burnishing, ballizing, mandrelizing, ring coining, and shot peening, have enjoyed varying levels of success in providing the required life improvement. However, these systems have limitations which can only be overcome by the high interference coldworking processes available today.

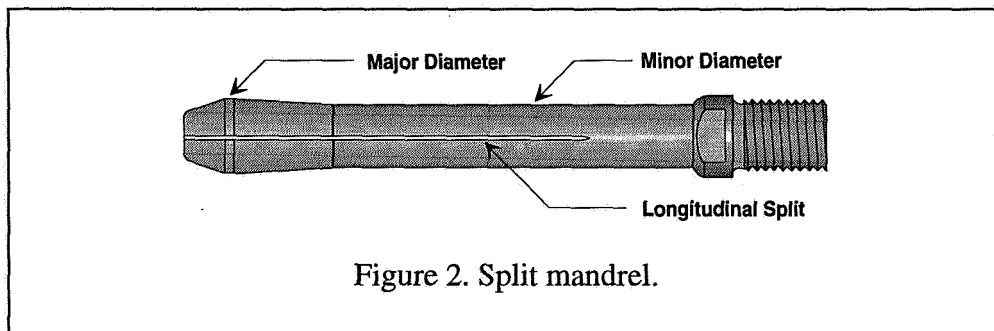
Boeing's (BCAC) Materials Research & Development has developed two high interference coldworking systems which provide significant life improvement at holes in metal structures exposed to cyclic loading. The split sleeve process, developed in the early 1970's, has gained acceptance by the aerospace industry as a valuable tool for fighting fatigue [1-3]. The main drawback of the sleeve system has been the high cost associated with disposable perishable tooling (split sleeves). A solution for this problem was the sleeveless split mandrel system developed by Boeing in the early 1980's [4-5].

As sometimes occurs with any newly developing technology, the fatigue life benefits obtained during the developmental phase were somewhat disappointing. In 1983, an evaluation [6] compared the split sleeve process with the new sleeveless system, using an early developmental mandrel. The results of this program concluded that the sleeveless system, though cost effective, provided somewhat less fatigue life improvement (Figure 1) than that provided by the sleeve system. It was proposed that "the higher retained expansion found in the holes coldworked with the sleeveless system may have been due to plastic flow into the mandrel slots" [6]. The results obtained in that program were indicative of the state of the art at that time. The tooling used in that program is no longer used for split mandrel coldworking. The tooling system in use today produces fatigue life results substantially different from that published in the 1983 study. Although no data has been published in the open literature, significant data exists at Boeing, Bristol Aerospace (under oversight of Canadian Air Forces), U.S. Air Force (Wright Laboratories), and WCI, demonstrating similar life improvement for both the split mandrel and split sleeve processes. As a result of this data, the sleeveless system has been incorporated into the Boeing 777, Automated Spar Assembly Tool (ASAT), and in a similar robotics environment at Bristol Aerospace (F-5 re-wing program).



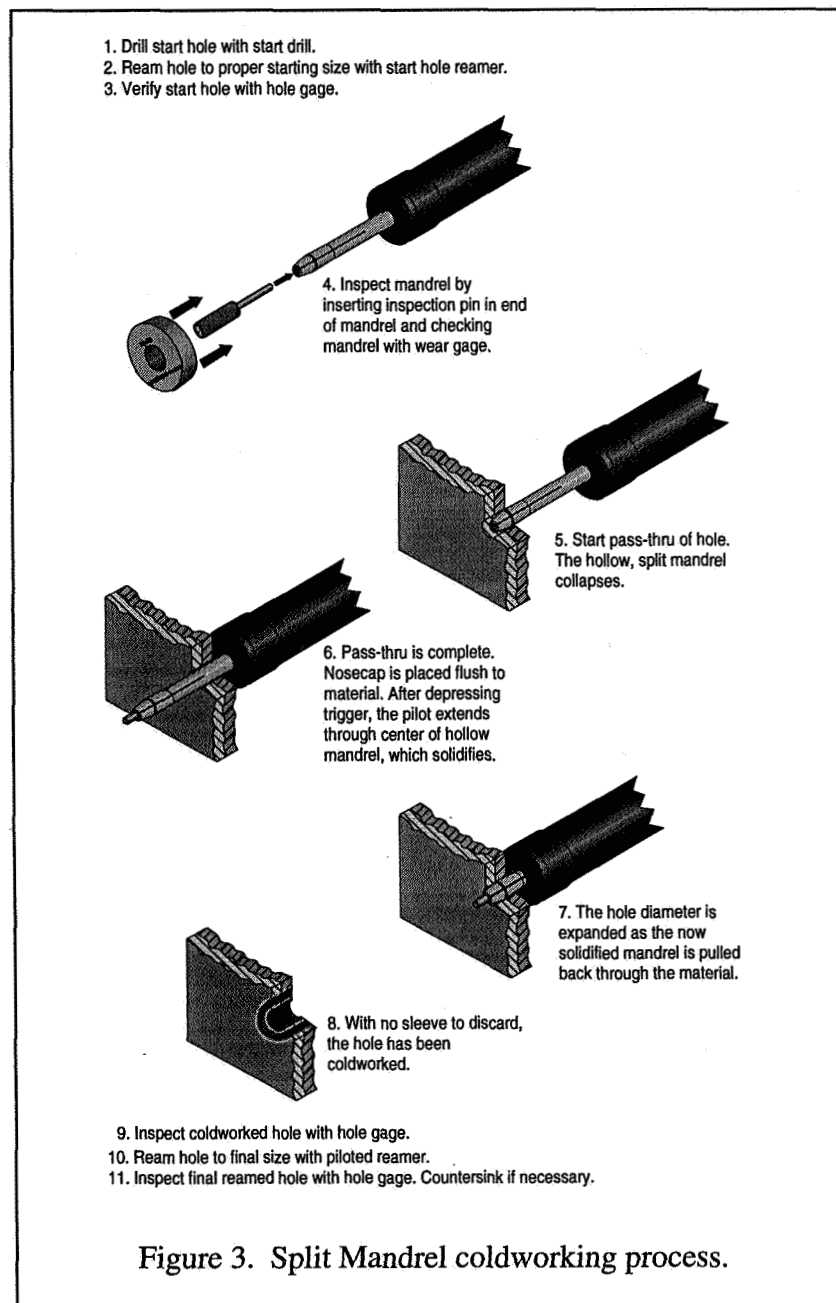
## PROCESS DESCRIPTION

The mechanism by which fatigue life gain is achieved, by any coldworking process, is due to the introduction of compressive residual stresses in the material surrounding the hole. These stresses are created by the radial expansion of material (plastically), as the mandrel is drawn into the hole and the creation of a large compressive hoop stress adjacent to the hole ( $\approx$  equal to the yield strength of the material), in combination with a tensile stress (required for equilibrium of forces) located some distance away from the hole after the mandrel is withdrawn. The net effect of the residual compressive stress is to lower the stress ratio ( $\sigma_{\min}/\sigma_{\max}$ ) and the resulting damage associated with predominantly tensile cyclic loads.



The only difference between the split mandrel (SpM) and split sleeve (SpSI) system for coldworking holes is the design of the tooling system utilized in performing the work. The split mandrel process

utilizes a collapsible mandrel (Figure 2) with a sliding pilot shaft extending through the mandrel which serves to solidify the mandrel prior to coldworking a hole. With the pilot retracted, the mandrel is partially collapsible, allowing insertion into the hole. When the puller unit is actuated, the pilot extends and solidifies the mandrel. The mandrel is then pulled through the hole (Figure 3). Boelube, a Boeing developed lubricant, is used to lower the frictional forces resulting from the mandrel sliding against the hole during the coldworking process. The proper amount of lubrication (approximately one drop) is automatically applied to the mandrel after each cycle as it re-extends. Boelube is a lubricant used in other machining steps such as pre- and post-reaming of coldworked holes. Clean-up is minimized, since less than one drop is required per hole,.



## TEST PROGRAM

Two groups of experiments were performed in order to quantify the fatigue life benefits obtained when using either coldworking process, and facilitate a comparison of these systems. The open hole specimens used in these experiments were manufactured from 2024-T3 and 7075-T6 aluminum plate, double disk ground to a material thickness of 0.250. One group of tests (Table 1) was performed under cyclic load control, at constant amplitude, with a gross maximum stress level of 30 ksi and a stress ratio of 0.1. The process parameters examined included the minimum and maximum applied expansion levels following the established applicable process standard. In the second group of tests, similar specimens were tested (1/4" diameter hole) at differing maximum stress levels ( $R=0.1$ ), to obtain information regarding process performance under a range of load conditions.

**Table 1. Specimen Configuration**

Material	Hole Size			
	5/32	3/16	1/4	17/64
2024-T3 [10]			0.250" x 1.50"	
7075-T651 [9]	0.250" x 1.0"	0.250" x 1.0"	0.250" x 1.50"	0.250 x 1.50"

## RESULTS AND DISCUSSION

In order to objectively compare the SpM and SpSl coldworking processes, it is necessary to compare fatigue life test results at identical test conditions. Obviously, specimen material, test geometry, machining quality, and applied loads, need to be the same. Additionally, the amount of coldwork applied to each specimen should be the same.

The amount of coldwork performed on a hole is controlled by the amount of applied expansion ( $E_a$ ) used to work the hole. Since the split sleeve experiences a great deal of deformation during the coldworking process, the "applied expansion" used in the split sleeve process is not necessarily the true expansion that is delivered to the hole. This does not hold true for the SpM system, since there is no sleeve to deform.  $E_a$  is calculated by:

$$E_a = \frac{A - B}{B} \times 100$$

$$A = \text{Mandrel Major Diameter} + 2 \times \text{sleeve thickness (Split Sleeve)}$$

or:

$$\text{Mandrel Major Diameter (Split Mandrel)}$$

$$B = \text{Start Hole Diameter}$$

Retained expansion ( $E_r$ ), a ratio of the post coldwork hole diameter to the initial hole diameter, is also a measure of the amount of coldwork performed on the hole. This value measures the actual material response to the coldworking process and is unaffected by different coldworking processes. The equation for evaluating the amount of retained expansion (for any process) is as follows:

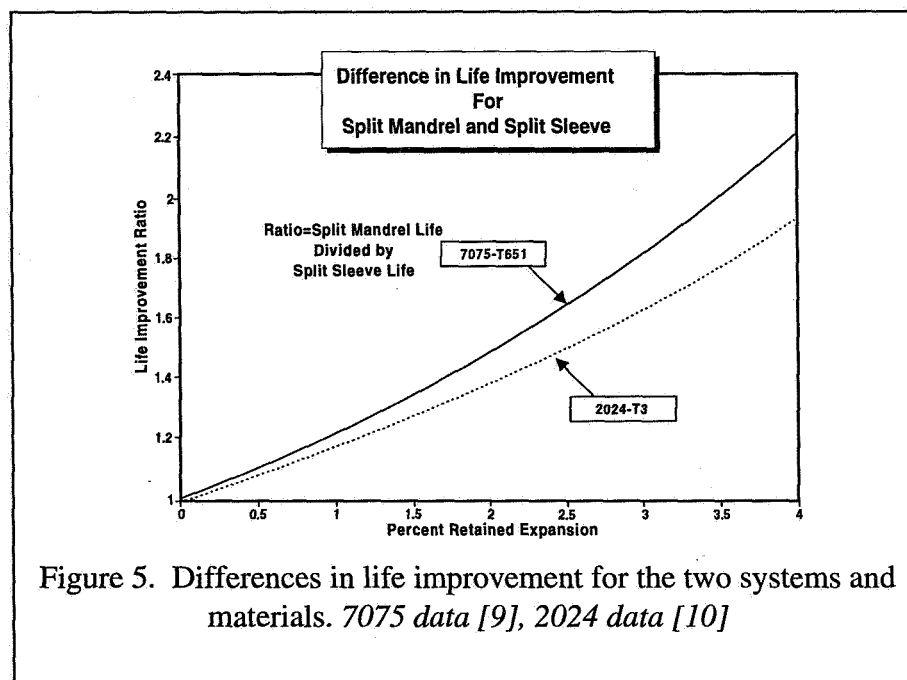
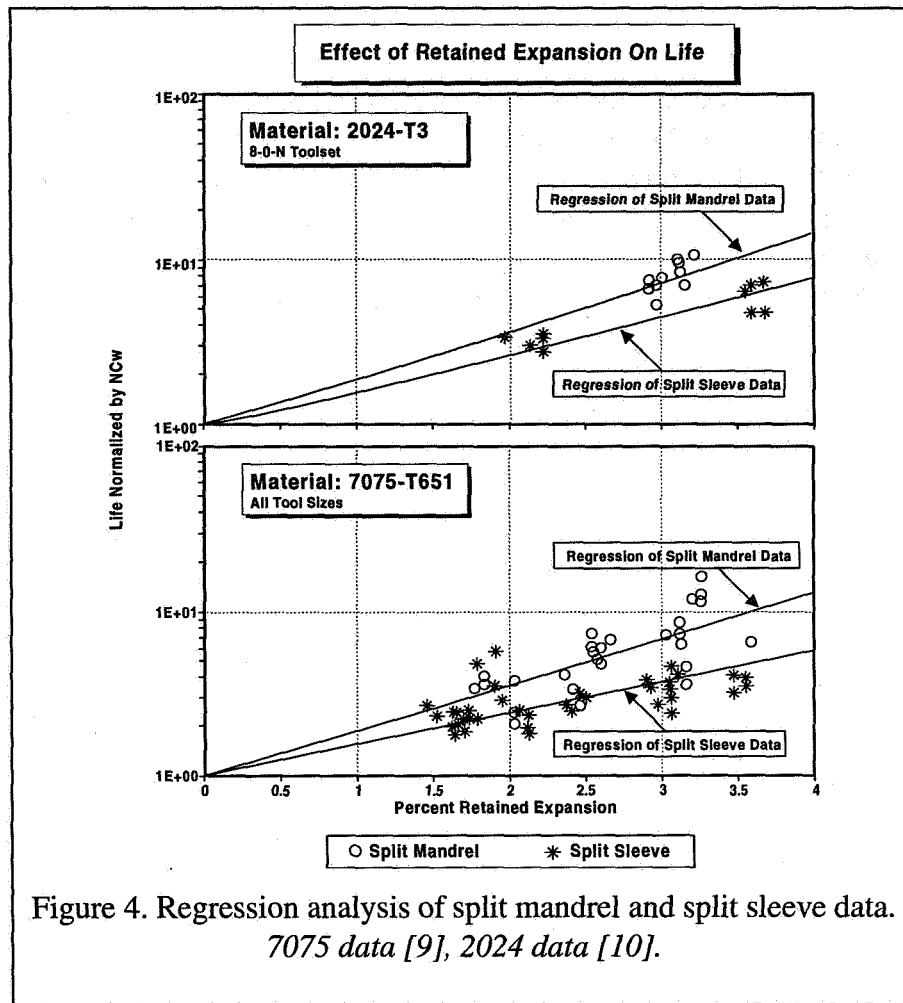
$$E_r = \frac{C - B}{B} \times 100$$

C = Measured Hole Diameter After Coldworking

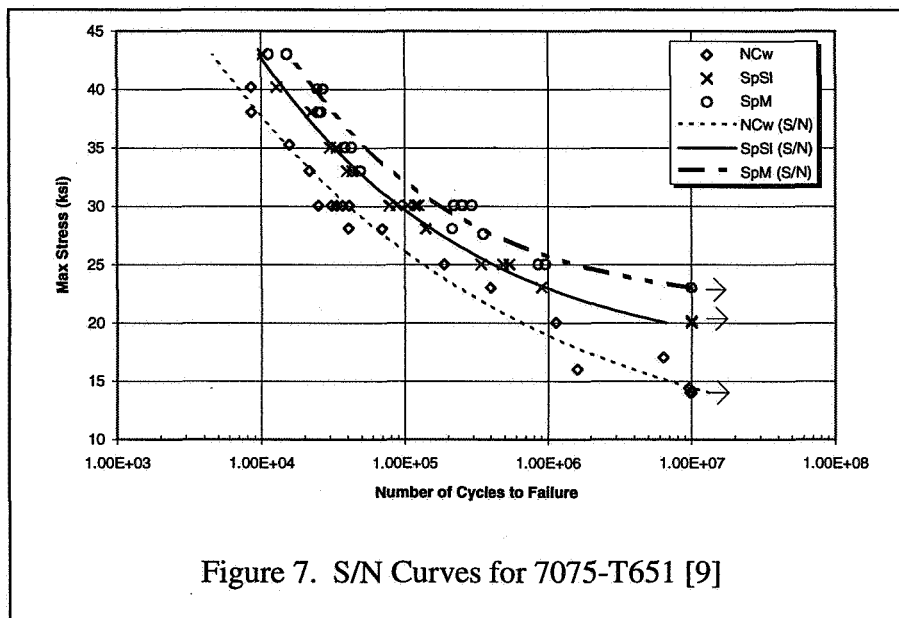
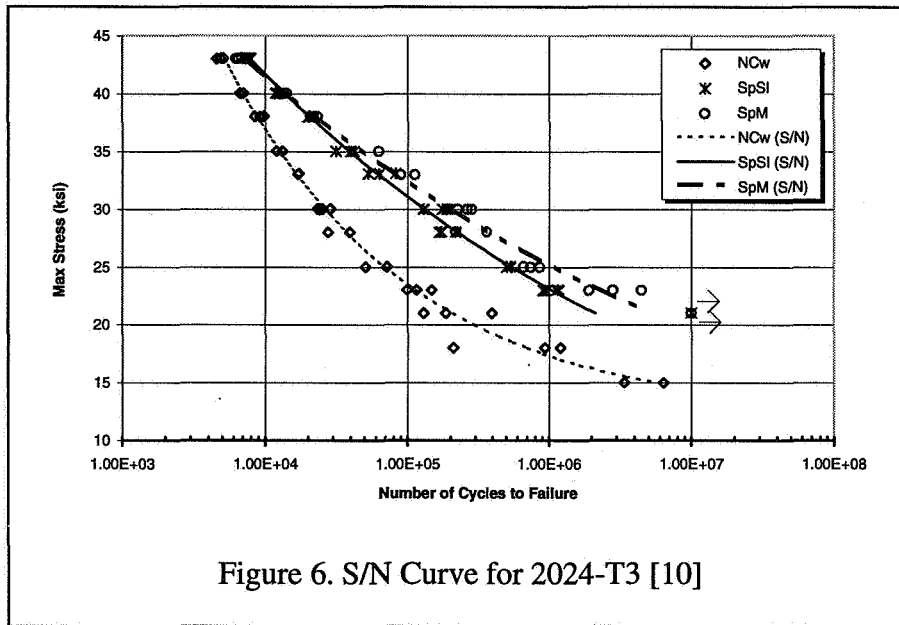
B = Start Hole Diameter

Due to the deformation of the split sleeve during the coldworking process, the relationship between  $E_a$  and  $E_r$  is generally different for each coldworking process. Consequently, the retained expansion is a more fundamental and appropriate measure to use in evaluating the efficacy of any coldworking process and in comparing the split mandrel and split sleeve processes.

The 2024-T3 and 7075-T651 coldworked specimen life data presented in Figure 4 has been normalized by the non-coldworked (NCW) baseline life for each material and hole size. Unlike the data from the 2024 material (containing one hole size), the data from the 7075-T651 material was generated at four hole diameters. Normalizing of the 7075 data at the corresponding hole diameter decreases any effect of hole diameter on the observed data trends. All of the data presented clearly reflects a trend of longer fatigue life with increased retained expansion. The data also clearly shows an increase in fatigue life for the split mandrel process, over the split sleeve process. Above an  $E_r$  level of approximately 2.5%, there is a clear discernible increase in life due to split mandrel coldworking over that due to split sleeve coldworking. Note that there is a marked similarity in the relationship between normalized life and retained expansion for both materials. Figure 5 shows the ratio of SpM life based upon the Figure 4 linear regression lines (log life versus retained expansion) for both coldworking processes. This allows quantification of the life improvement benefits for either system. The resulting graphic demonstrates a somewhat higher ratio for the 7075-T6 material, but the difference between the two materials is not large.



Additional tests were run at stress levels above and below 30 ksi for 0.250" diameter holes with the applied expansion levels at or near the maximum specification values. The resulting data are plotted in Figure 6 (2024-T3) and Figure 7 (7075-T6) along with regression analysis curves for the data sets of the split sleeve process, split mandrel process, and non-coldworked specimens. Again, the data reflect an increased effectiveness of the split mandrel as compared to the split sleeve process. The increased effectiveness, although not as distinct in the 2024-T3 material, is observed at all stress levels and serves to demonstrate that the SpM process is equal or superior to the split sleeve coldworking process for all loading levels.



## MANUFACTURING CONSIDERATIONS

In addition to the fatigue life benefits obtained with any fastener hole coldworking system, another facet of importance is the cost (time and materials) of implementing the process. Boeing developed the sleeveless process as a means to lower manufacturing costs. The split mandrel system has been used in production on every Boeing produced hardware system since 1983, and has been chosen for use in an automated environment on the new ASAT (Automated Spar Assembly Tool) machine for the manufacture of the new 777 wing. Additionally, Bristol Aerospace has recently begun the manufacture of improved wing sets for the F-5 using automated split mandrel coldworking. In each case, economic considerations were the basis for the choice of the split mandrel system, since both the split mandrel and split sleeve systems provide comparable life improvement. Both companies had investigated the sleeve process in automated and non-automated environments and found it to be impractical and cost prohibitive. This was mainly due to the deceptively simple task of selecting, orienting, placing and removing the disposable sleeve.

The cost of coldworking a hole using the split sleeve system varies from 0.50¢ to \$17.00, depending upon sleeve size, length, etc. In deleting the sleeve cost, the split mandrel system will coldwork a hole at 0.05¢ per hole, without the burden of expensive supporting capital equipment. The only difference in the capital equipment between either process is the automatic lubricator and puller unit utilized in the split mandrel system. The split mandrel capital tooling detail parts are interchangeable (in many cases) with those of the sleeve system. This allows the capital equipment costs for either system to be virtually the same due to economy of scale.

Additional cost savings when using the SpM system are realized by reducing the amount of processing time required for each hole. Roughly four seconds are required for a robot, or operator, to coldwork a hole and move to the next. With the split sleeve process, there is the additional processing time required for installing and disposing of the split sleeve (multiplying the time by a factor of 3).

## CONCLUSIONS

Through its simplicity of design, the split mandrel process is an efficient, cost effective system for high interference coldworking of holes. The data collected in this research program demonstrate that the split mandrel and split sleeve processes increase the fatigue life of holes significantly, and that the life improvement obtained with the split mandrel process is at least as good as that provided by the split sleeve process. The combination of effectiveness and economic advantages of the split mandrel process over other coldworking processes should serve as a driving force for the aerospace community to turn to the split mandrel system as the preferred solution to high manufacturing costs, in both time and materials, often associated with the coldworking of critical holes in aircraft metallic structures.

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